ARKIV FÖR FYSIK Band 19 nr 14

Communicated 7 December 1960 by B. Edlén and T. Gustafson

Relative intensities of gamma rays from the reaction F^{19} $(p, \alpha\gamma)$ O^{16}

By Lars Ask

With 8 figures in the text

ABSTRACT

The relative intensities of the 6.14, 6.92 and 7.12 MeV gamma rays have been measured for proton energies up to 2.63 MeV. A three-crystal-pair spectrometer has been used with an energy resolution of 4 %, permitting the two 7 MeV components to be resolved.

Introduction

In the bombardment of F^{19} by protons, Ne^{20} is formed in excited states, which show a high probability of decay by alpha emission to states of O^{16}. This decay gives five groups of alpha particles in the transitions to the ground state and four excited states in O^{16} and all of them show resonance effects [1]. The two most energetic (α_0 and α_π), which leave O^{16} in the ground state ($J = O^+$) and the first excited, nuclear-pair-emitting state ($J = O^+$) respectively, have in general the same resonances. These are different from the resonances shown by the three remaining alpha-particle groups (α_1, α_2, and α_3), giving rise to gamma-emitting states at 6.14 (3^-), 6.92 (2^+) and 7.12 (1^-) MeV with the gamma rays γ_1, γ_2 and γ_3. At proton energies lower than 1.4 MeV this reaction has been thoroughly investigated and it is stated that the relative intensities of the alpha-particle groups vary greatly with the bombarding energy. For the short-range alpha particles, Burcham and Freeman [2] have measured the relative intensities at some resonances below 950 keV, without being able to separate the α_2 and α_3 groups, which was later done by Freeman [3] and by Chao *et al.* [4], who extended the measurements to all the most prominent resonances for proton energies lower than 1380 keV.

The existence of at least two gamma rays in the fluorine radiation was first shown by Walker and McDaniel using a magnetic pair spectrometer [5]. They also gave the intensity ratio of these components in thick target radiation at different proton energies. The same quantities have been measured at individual resonances below 1380 keV by Rasmussen *et al.* [6] and by Sanders [7,8]. Correcting for angular distributions [9, 10], Barnes [11] has calculated partial widths for certain levels in Ne^{20} using some of the measurements mentioned above.

At higher proton energies the reaction has not been investigated to such a great extent. The yield of gamma radiation of energy greater than 3 MeV has been meas-

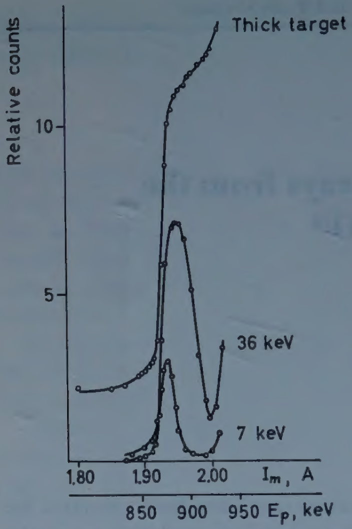

Fig. 1. Yield of gamma radiation from $F^{19}(p, \alpha\gamma)O^{16}$ at $E_p = 874$ keV from a thick target and two thin targets with various thicknesses.

ured [12, 13] for proton energies up to 5.2 MeV, without measuring the relative contributions of the three components. One measurement of the ratio $(\gamma_2 + \gamma_3)/\gamma_1$ has been done by Bent *et al.* [14] at $E_p = 3.7$ MeV using a thick CaF_2 target. From the excitation curve it is seen that the yield increases very sharply at about 2 MeV and as this strong reaction is a convenient source of 6- and 7-MeV gamma radiation it is of importance to know its composition. In order to estimate the composition of the 7-MeV radiation, Swann and Metzger [15] measured the relative intensities of the α_2- and α_3-groups, since it was impossible to separate the corresponding 6.92 and 7.12 MeV gamma rays, for proton energies between 1.90 and 2.85 MeV.

By using a three-crystal-pair spectrometer it has been possible in the present work to separate the two 7 MeV components and then to determine the relative intensities of the 6.14, 6.92, and 7.12 MeV gamma rays at the strongest resonances and at some other energies below $E_p = 2.63$ MeV.

Experimental arrangements

The proton beam used in the experiments was produced by the van de Graaff generator at the Department of Physics, University of Lund [16]. The beam passed through an analysing magnet and was bent 28° at proton energies below 2 MeV and 20° at higher energies. From the exit slit of the magnet a signal was taken for controlling the generator potential by corona stabilization. The spread in beam energy was estimated from the slope of the thick target yield curve at $E_p = 874$ keV to be less than 0.4 per cent (Fig. 1). As a measure of the proton energy, the current through the analysing magnet was used. Calibration was made using the excitation curve for the reaction and the energy values given in [1]. As targets CaF_2 crystals and CaF_2 evaporated on tantalum were used. Various thicknesses of the targets were employed: at 340 keV a thick target; at the resonances below 1.4 MeV, thin targets about 7 keV thick at 874 keV; at the other energies thin targets about 20 keV at

2 MeV. The thicknesses were measured at 874 keV by comparison of the area under the thin-target yield curve at this resonance with the step in the thick-target yield curve at the same resonance [17] (Fig. 1). The yield curves were taken at 90° to the beam with a sodium iodide scintillation counter.

The gamma ray spectra were measured at an angle of 90° to the proton beam with a three-crystal-pair spectrometer. This has been described earlier [18]. For a monoenergetic gamma radiation of energy greater than 1.02 MeV it gives a pulse height distribution with only one peak, corresponding to an energy 1.02 MeV lower than the incident gamma energy E_γ, and a low-energy tail. The choice of the dimensions of the central crystal and the collimation of the incident radiation affects the width of the peak and the height of the tail. In this work it was desirable to have a very good energy resolution and a low tail. From the earlier investigation of the spectrometer [18] it is seen that this is obtained by using a long central crystal and good collimation. The central crystal was 3 inches long and $1\frac{1}{2}$ inches in diameter, coupled to a Du Mont photomultiplier 6292. The side crystals were 4 inches long and 5 inches in diameter and were coupled to Du Mont 6364 photomultipliers. They were shielded against direct irradiation from the target by 100 mm lead and 30 mm iron. The incident radiation was collimated in a conical collimator of 175 mm length and diameters of 18 and 10 mm. The distance from the target to the collimator was 100 mm.

The gamma rays at 6.92 and 7.12 MeV are very close in energy and in order to be able to separate these, it was desirable to spread the pulse height distribution over more channels than were available in the analyser. To do this, a biased amplifier, which expands the upper part of the pulse spectrum, was included in the multichannel analyser. The bias and amplification of this expander were chosen to give an expansion factor of about two. In this way it was possible to get a clearer picture of the fine structure of the pulse height distribution near 7 MeV. The multi-channel analyser used was of the Hutchinson-Scarrot type and it was calibrated with 2.62 MeV RdTh, and the 6.14 MeV fluorine radiation.

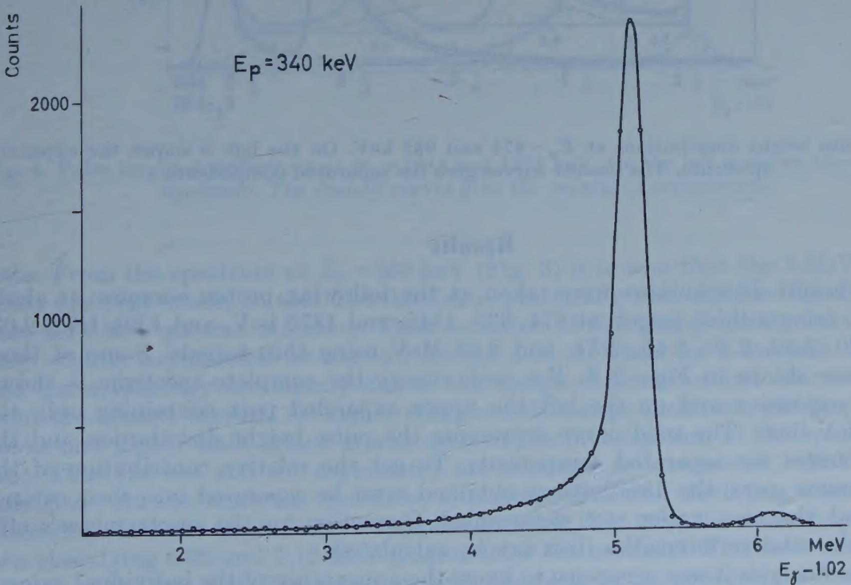

Fig. 2. Pulse height distribution without expander at $E_p = 340$ keV.

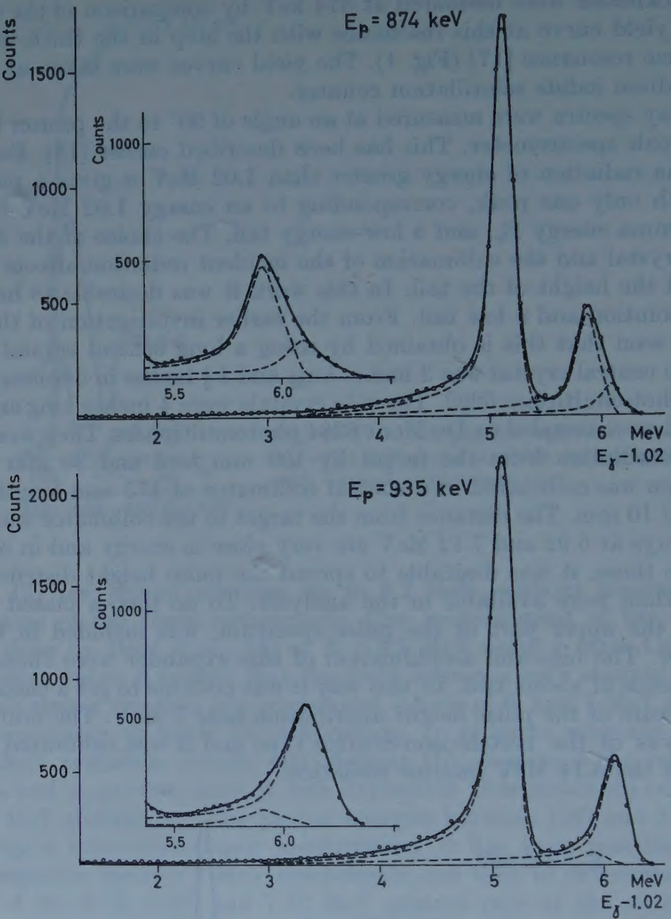

Fig. 3. Pulse height distributions at $E_p = 874$ and 935 keV. On the left is shown the expanded spectrum. The dashed curves give the separated components.

Results

Pulse height distributions were taken at the following proton energies: at about 400 keV, using a thick target, at 874, 935, 1348, and 1375 keV, and 1.69, 1.95, 2.03, 2.10, 2.20, 2.32, 2.40, 2.45, 2.51, and 2.63 MeV using thin targets. Some of these spectra are shown in Figs. 2–7. For each energy the complete spectrum is shown without expansion and on the left the upper expanded part containing only the two 7 MeV lines. The solid curve represents the pulse height distribution and the dashed curves the separated components. To get the relative contribution of the three gamma rays, the distributions obtained must be separated into their components and the area under each determined. Correcting for the spectrometer's efficiency, the relative intensities then can be calculated.

For the analysis it was necessary to know the appearance of the individual gamma

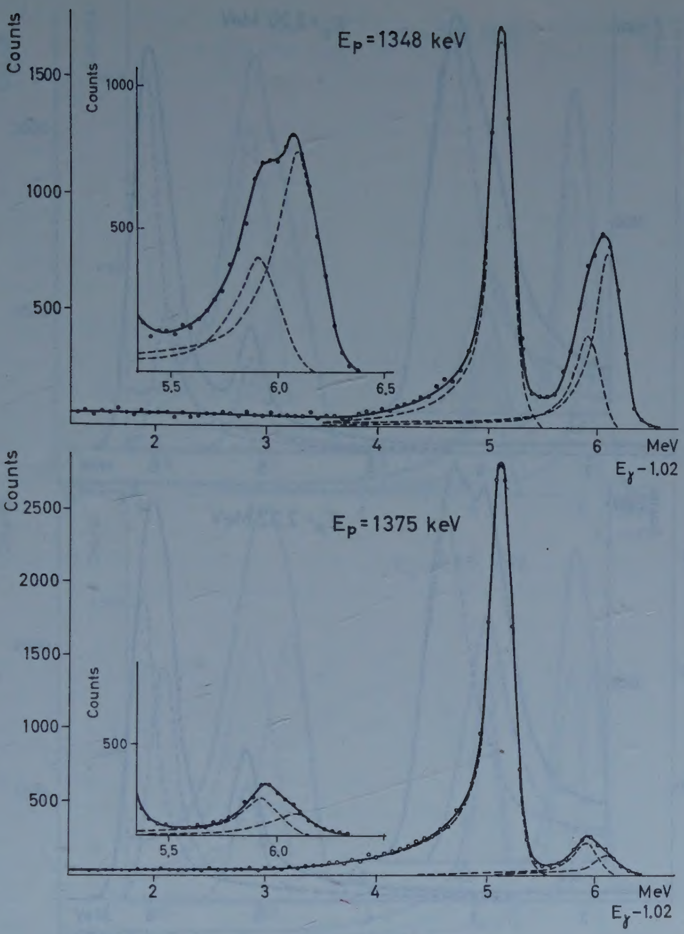

Fig. 4. Pulse height distributions at $E_p = 1348$ and 1375 keV. On the left is shown the expanded spectrum. The dashed curves give the separated components.

lines. From the spectrum at $E_p = 340$ keV (Fig. 3) it is seen that the 7-MeV components are very weak, so this distribution is practically the response function for a pure 6.14-MeV gamma radiation. Thus radiation of this energy yields a sharp peak, only slightly asymmetric at the low energy side, followed by a low tail. This tail and the asymmetry are mainly due to the escape of electrons and bremsstrahlung from the central crystal. At higher energies this escape increases, yielding broader peaks and higher tails, which is also seen in the investigation of the spectrometer [18]. Thus the tail and the asymmetry are expected to increase at 7 MeV gamma radiation. At the analysis, therefore, a response function deviating somewhat in these respects from the 6.14-MeV response function, but with the same shape for the two close-lying 6.92 and 7.12-MeV gamma lines was assumed. This curve was drawn for one of the two 7-MeV components with the peak in the appropriate channel and

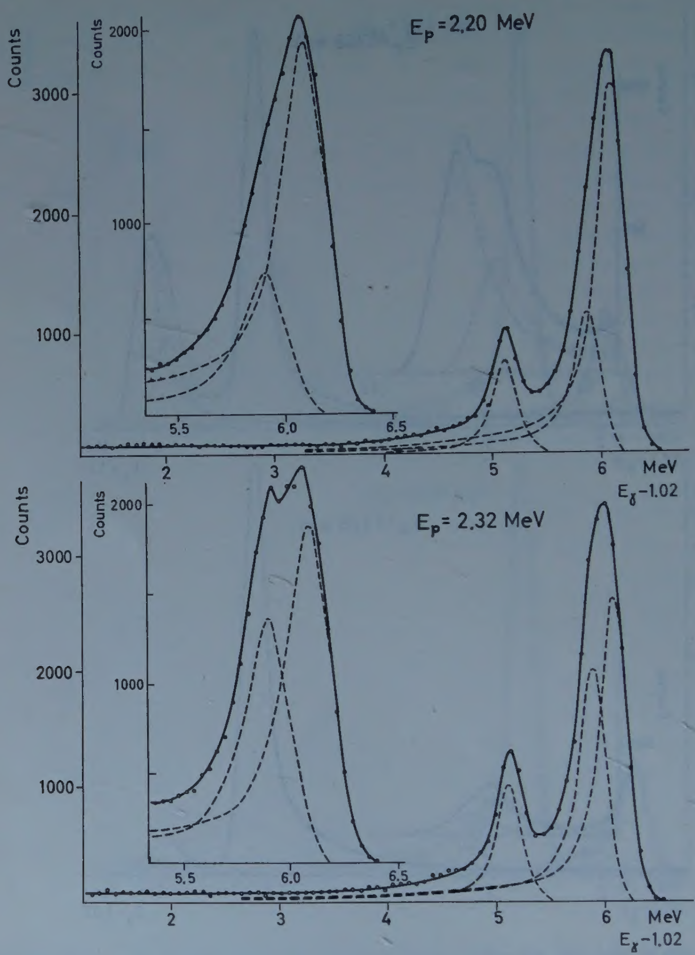

Fig. 5. Pulse height distributions at $E_p = 2.20$ and 2.32 MeV. On the left is shown the expanded spectrum. The dashed curves give the separated components.

a certain maximum value assumed. By subtraction, the curve for the other component was obtained. When, by trial and error, this new curve came with its peak in the right channel and had the same shape as the first assumed one, the separation of the two components was said to be right. Thus the conditions to be satisfied in the analysis are that the two gamma lines will have their peaks at the right energy and that they will have the same response function. If the 6.92- and 7.12-MeV gamma lines obtained from the analysis are drawn normalized to the same peak value, it is possible to estimate the biggest deviation from the mean value of the response function, to be about 7 %, which is taken to be the uncertainty in the analysis. Subtraction of the sum of the two 7-MeV components from the experimental distribution gave the 6.14-MeV curve. Not all of the spectra analysed in this manner are shown. In Figs. 3 and 4 are seen the spectra for proton energies lower than 1.4 MeV,

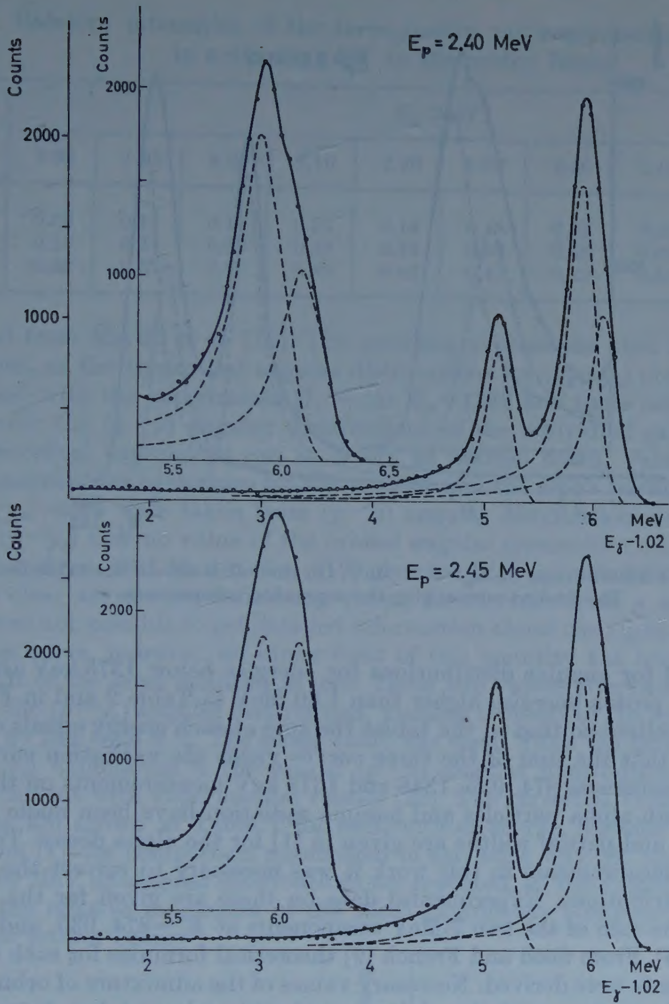

Fig. 6. Pulse height distributions at $E_p = 2.40$ and 2.45 MeV. On the left is shown the expanded spectrum. The dashed curves give the separated components.

where comparison with earlier measurements can be made. For higher energies only some typical examples of the analysis are shown in Figs. 5, 6 and 7. In these the variation in the appearance of the pulse height distribution with changing contributions of the three components is clearly demonstrated.

From the spectra without the expander amplifier the relative intensities of γ_1 and the sum $(\gamma_2 + \gamma_3)$ were calculated by determining the areas under corresponding curves and correcting for the spectrometer's efficiency. This correction is about the ratio of the cross-sections for pair production at 6 and 7 MeV and it was taken from the efficency curve for the spectrometer [18]. From the spectra with expander the intensities of the 6.92- and 7.12-MeV gamma lines were obtained by taking the ratio between the peak values. The relative intensities of the three components thus ob-

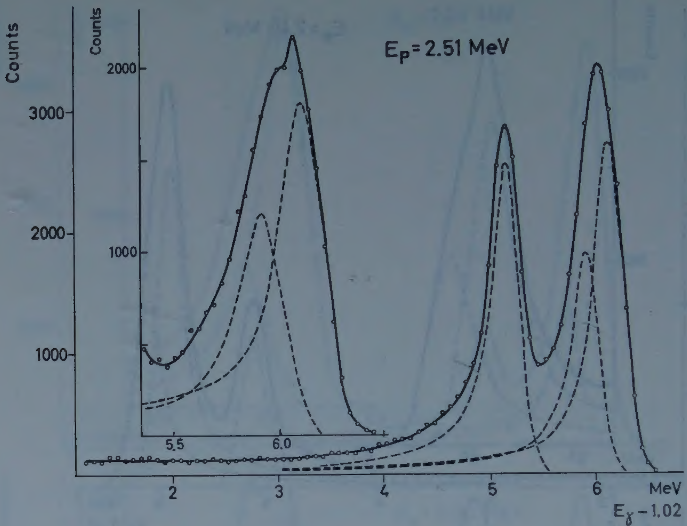

Fig. 7. Pulse height distributions at $E_p = 2.51$ MeV. On the left is shown the expanded spectrum. The dashed curves give the separated components.

tained corrected for angular distributions for energies below 1375 keV are given in Table 1 and for proton energies higher than 1.69 MeV in Table 2 and in Fig. 8. The values are normalized so that in the tables the sum at each energy equals one and in the diagram so that the sum of the three curves yields the excitation curve.

At the four resonances 874, 935, 1348 and 1375 keV measurements on the relative intensities of both alpha particles and gamma radiation have been made earlier by several workers and partial widths are given in [1] for the alpha decay. To compare these with the meaurements in this work it was necessary to correct the latter for the angular distributions. Experimental data on these are given for the 6.14 MeV radiation and the sum of the two 7-MeV components at $E_p = 874$, 935, and 1375 keV by Sanders [7, 8]. From Seed and French [9] theoretical formulas for each of the two 7-MeV components were derived. Necessary values of the admixture of orbital angular momenta for the protons and the alpha particles have been taken from the same

Table 1. Relative intensities of the three gamma ray components in F^{19} $(p, \alpha\gamma)$ O^{16}.

The values in parentheses are taken from [1].

E_p (keV)	E_γ (MeV)		
	6.14	6.92	7.12
874	0.69 (0.68)	0.23 (0.24)	0.08 (0.08)
935	0.77 (0.76)	0.03 (0.03)	0.20 (0.21)
1348	0.53 (0.54)	0.15 (0.14)	0.32 (0.32)
1375	0.88 (0.87)	0.07 (0.08)	0.05 (0.05)

Table 2. Relative intensities of the three gamma ray components in $F^{19}(p, \alpha\gamma)O^{16}$ in a direction 90° to the proton beam.

E_γ (MeV)	E_p (MeV)									
	1.69	1.95	2.03	2.10	2.20	2.32	2.40	2.45	2.51	2.63
6.14	0.52	0.12	0.14	0.21	0.14	0.18	0.23	0.29	0.39	0.37
6.92	0.15	0.21	0.16	0.21	0.24	0.35	0.48	0.36	0.24	0.25
7.12	0.33	0.67	0.70	0.58	0.62	0.47	0.29	0.35	0.37	0.38

work and from Martin *et al.* [19]. The resulting expressions were then used for the corrections, as the theoretical angular distributions for $(\gamma_2+\gamma_3)$ obtained from them agreed well with the experiments [7, 8]. At $E_p=1348$ keV there are no experimental results over the $(p-\gamma)$ angular distributions of the individual gamma lines. However, theoretical expressions can as before be written down. Values of the orbital angular momentum admixture for the protons and the alpha particles in the $(p-\gamma_2)$ and $(p-\gamma_3)$ cases were taken from $(p-\alpha)$ angular distribution measurements [10]. For the $(p-\gamma_1)$ case no value of the orbital angular momentum mixture of the alpha particles is given. But Martin *et al.* [19] give the $(\alpha_1-\gamma_1)$ correlation pattern, which shows a clear asymmetry indicating strong interference from a neighboring state. Thus it was not possible to get detailed information about the alpha-particle mixture. From this curve, however, an upper limit of this quantity has been estimated. The lower limit of the same quantity is zero. These two values give two different expressions for the $(p-\gamma_1)$ angular distribution, yielding two sets of the relative intensities, differing by less than 5 %. The mean value was used. From the three $(p-\gamma_1)$, $(p-\gamma_2)$ and $(p-\gamma_3)$ expressions a theoretical $(p-\gamma)$ angular distribution was derived in good agreement with experimental results [20]. The corrected values of the relative intensities are shown in Table 1 for each proton energy together with the vlaues taken from [1], for comparison normalized in the same way. At the proton energies above 1.69 MeV no angular distributions are reported, so the values given in Table 2 refer to the relative intensities of the three gamma-ray components in a direction 90° to the proton beam.

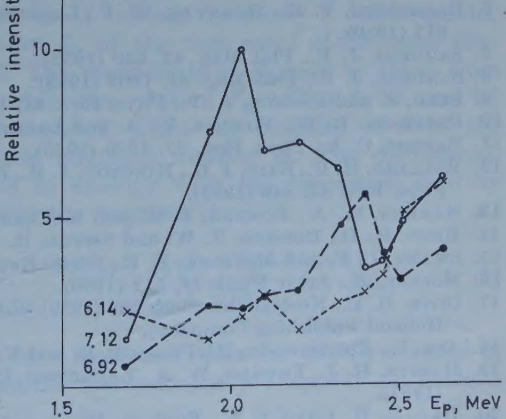

Fig. 8. Relative intensities of the three components at proton energies between 1.69 MeV and 2.63 MeV.

Discussion

In earlier measurements on the gamma radiation the two 7-MeV components have not been separated. Their relative intensities can, however, be derived from investigations of the alpha particles. In Table 1 a comparison can be made between the values of the relative intensities obtained from measurements of well-separated alpha-particle groups and the values given in the present investigation. The agreement is very good, providing a check on this method. The error in the present values is estimated from the statistical error, from the uncertainty in the analysis and in the determination of the areas to be about ±10 %. An advantage of this method is that the whole spectrum is recorded in the same run, so that any instabilities in the electronics are common to all three components and thus do not affect the relative intensities.

The results obtained at proton energies between 1.95 MeV and 2.63 MeV can be compared with the measurements on the alpha particles made by Swann and Metzger. Such a comparison shows an evident discrepancy between the two investigations, in that the curve for the α_2-group given by Swann and Metzger is higher than the corresponding 6.92-MeV curve in this work. An explanation of this could be that in this region the levels in Ne^{20} were very like each other, therefore giving rise to the same type of $(p-\alpha)$ angular distributions. If these were such that the α_2-group has a peak at 90°, while the α_3-group has a peak at 0°, then a measurement at 90° gives too high a contribution of the α_2-group. This type of angular distribution is shown by the resonances at 874, 1348, and 1375 keV, which all give 2^- levels in Ne^{20} [10].

ACKNOWLEDGEMENTS

The author wishes to express his sincere gratitude to Dr. S. A. E. Johansson for his proposal of this investigation and for valuable discussions, and to Professor S. von Friesen for his kind interest in the work and for making good experimental facilities available.

REFERENCES

1. Ajzenberg-Selove, F. and Lauritsen, T., Nucl. Phys. *11*, 278 (1959).
2. Burcham, W. E. and Freeman, Joan M., Phys. Rev. *75*, 1756 (1949).
3. Freeman, Joan M., Phil. Mag. *41*, 1225 (1950).
4. Chao, C. Y., Tollestrup, A. V., Fowler, W. A. and Lauritsen, C. C., Phys. Rev. *79*, 108 (1950).
5. Walker, R. L. and McDaniel, B. D., Phys. Rev. *74*, 315 (1948).
6. Rasmussen, V. K., Hornyak, W. F., Lauritsen, C. C. and Lauritsen, T., Phys. Rev. 77, 617 (1950).
7. Sanders, J. E., Phil. Mag. *43*, 630 (1952).
8. Sanders, J. E., Phil. Mag. *44*, 1302 (1953).
9. Seed, J. and French, A. P., Phys. Rev. *88*, 1007 (1952).
10. Peterson, R. W., Fowler, W. A. and Lauritsen, C. C., Phys.Rev. *96*, 1250 (1954).
11. Barnes, C. A., Phys. Rev. *97*, 1226 (1955).
12. Willard, H. B., Bair, J. K., Kington, J. B., Hahn, T. M., Snyder, C. W. and Green, F. P., Phys. Rev. *85*, 849 (1952).
13. Ranken, W. A., Bonner, T. W. and McCrary, J. H., Phys. Rev. *109*, 1646 (1958).
14. Bent, R. D., Bonner, T. W. and Sippel, R. F., Phys. Rev. *98*, 1237 (1955).
15. Swann, C. P. and Metzger, F. R., Phys. Rev. *108*, 982 (1957).
16. Möller, E., Arkiv Fysik *16*, 511 (1960).
17. Gove, H. E., Nuclear Reactions 292 (1959) (Edited by Endt, P. M. and Demeur, M.; North-Holland Publishing Company).
18. Ask, L., Erlandsson, B., Persson, B. and Valli, K., Arkiv Fysik (1961).
19. Martin, H. J., Fowler, W. A., Lauritsen, C. C. and Lauritsen, T., Phys. Rev. *106*, 1260 (1957).
20. Day, R. B., Chao, C. Y., Fowler, W. A. and Perry Jr, J. E., Phys. Rev. *80*, 131 A (1950).

Tryckt den 18 mars 1961

Uppsala 1961. Almqvist & Wiksells Boktryckeri AB